

Tropical Cyclone Genesis and Sudden Changes of Track and Intensity in the Western Pacific

PI: Bin Wang
Co-PI: Yuqing Wang and Tim Li
Department of Meteorology and
International Pacific Research Center
University of Hawaii
2525 Correa Rd. HIG 367 Honolulu, HI 96822
phone: (808)956-2563 fax: (808) 956-9425 email: wangbin@hawaii.edu

Award Number: N00014-06-1-0303
<http://www.soest.hawaii.edu/~bwang>

LONG-TERM GOALS

The long-term goal of this project is to advance our understanding of the linkage between tropical cyclone (TC) sudden track and intensity changes and to identify precursors for such sudden changes in both the large-scale environment and storm-scale structure. Of particular interest are the physical mechanisms involved in sudden track and intensity changes and unique genesis and development processes in the western Pacific.

OBJECTIVES

The objective of this proposed study is to investigate large-scale environmental conditions and TC internal processes as well as their interactions that are responsible for TC genesis, sudden track changes, rapid intensification (RI) and storm-scale structure changes. Specific thrust areas include, (1) Mechanisms for unique cases of TC genesis, (2) Inner core asymmetric and symmetric structure changes and associated precursors before RI, (3) The linkage between the large-scale environment, sudden track and rapid intensity changes, (4) The processes controlling the formation of concentric eyewalls and annular structure.

APPROACH

Our approach is to integrate observational analysis, numerical modeling, and diagnostic analysis to identify and investigate the physical mechanisms responsible for TC genesis, RI and track changes. We are adopting a strategy of combining analysis of recent satellite products from Aqua and TRMM and performing idealized and realistic numerical experiments with COAMPS, OMEGA and TCM4 models. We are also applying diagnostic tools to study energetics, potential vorticity, angular momentum and heat and moisture budgets. The budget diagnostics will help elucidate internal asymmetric and symmetric dynamic processes in the core region that could alter the thermodynamic efficiency of the TC intensification. People involved are the PI, Co-PIs, PostDocs: Justin Ventham and Bo Yang and graduate students: Xiaqiong Zhou, Bing Fu, Tom Dunn and Christopher Chambers.

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WORK COMPLETED

Works completed in FY06 are summarized below:

- (1) The effect of internally generated inner core asymmetric structure on tropical cyclone intensity.
- (2) A possible mechanism for tropical cyclone rapid intensification: Effect of meridional shear of zonal environmental flow.
- (3) A multiply nested, movable mesh, fully compressible, nonhydrostatic tropical cyclone model - TCM4: Model description and development of asymmetries without explicit asymmetric forcing.
- (4) Environmental dynamical control of tropical cyclone Maximum Potential Intensity.
- (5) On sea surface roughness parameterization and its effect on tropical cyclone structure and intensity.
- (6) Tropical cyclone changes in the western north Pacific in a global warming scenario.
- (7) A case study of equatorial genesis.
- (8) Large scale flow patterns and their influence on the intensification rates of western north Pacific tropical cyclones.
- (9) Secondary eyewall formation in the presence of horizontal shear.
- (10) Climate variation and prediction of tropical cyclone intensification in the western north Pacific.

RESULTS

1. The effect of internally generated inner core asymmetric structure on tropical cyclone intensity. This study investigates how inner-core convective asymmetries affect TC intensity on an f-plane. We used a three-dimensional (3D) TC model and its axisymmetric (2D) version. Both have identical model vertical structure and use the same parameters and initial conditions. The presence of asymmetries in the 3D run reduces the TC final intensity by about 15% compared with the 2D run, suggesting the TC asymmetry is a limiting factor to the Potential Intensity (PI). The physical mechanism for the difference was found to be linked to a greater tilt of the eyewall in the 2D run. The tilted eyewall results in evaporatively driven downdrafts under the eyewall which dry and cool the sub-cloud layer inflow. This results in a greater entropy difference between the ocean and the boundary layer, leading to more energy into the TC from the underlying ocean and an ultimately more intense TC. Asymmetries developing in the 3D run mix PV from the eyewall to the eye, resulting in less tilt, weaker downdrafts and less air-sea entropy deficit under the eyewall. This reduces the final 3D TC intensity. The explicit “eddy diffusion” of the azimuthal mean angular momentum is larger than the parameterized lateral diffusion in the 3D run, suggesting an overall diffusive effect of the asymmetric eddies on the symmetric circulation.

2. A possible mechanism for tropical cyclone rapid intensification: Effects of meridional shear of zonal environmental flow. For strong El Nino events, Wang and Chan (2002) found enhanced tropical storm formation in the south-east quadrant of the western north Pacific (WNP) to be primarily due to enhanced cyclonic (anticyclonic) meridional shear of lower (upper) level zonal environmental flows, rather than the magnitude of the vertical shear. To understand the role of the identified meridional shear of zonal environmental flow in TC intensification, idealized numerical experiments were conducted using a high-resolution TC model with explicit moisture physics. In the numerical simulation, a weak initial vortex was embedded in the environmental flows with the identified shear

structure. The simulation results indicate that the given meridional shear enhances the intensification of the modeled TC by inducing TC inner-core asymmetries. The environmental zonal flow, acting as a quasi-steady wavenumber-two asymmetric forcing, continuously excites radially propagating inner-core asymmetries. Coupled with moist and boundary-layer processes, the axisymmetrization of asymmetries inside the initial radius of maximum wind accelerates the contraction of the radius of maximum wind and the organization of the inner-core convection, leading to a RI of the simulated TCs.

3. A multiply nested, movable mesh, fully compressible, nonhydrostatic tropical cyclone model - TCM4: Model description and development of asymmetries without explicit asymmetric forcing.

A newly developed, multiply nested, movable mesh, fully compressible, nonhydrostatic TC model – TCM4 is used to investigate how asymmetric structure develops in an initially axisymmetric TC without any explicit asymmetric forcing. The results show that the initial development of asymmetries results from the numerical finite-differencing scheme on a regular square grid system and time-splitting error associated with the horizontal advection. Convective heating associated with the inner core convection in a moist run produces an off-center local PV maximum in the mid-lower troposphere. The reverse of the radial PV gradient across this PV annulus exhibits barotropic instability, resulting in a rapid development of large amplitude asymmetries in the inner core region with low azimuthal wavenumbers. These asymmetries are characterized by vortex Rossby waves. The physical modes are slightly modified by quasi-stationary computational asymmetries. Although the amplitude of the computational modes is small compared to the physical modes, interpretation of the asymmetries in the inner core region at any given time, especially the wavenumber-two component, needs caution. We have found no indication of contribution of inertial instability in the outflow layer to the development of asymmetries in the inner core region of our simulated storm.

4. Environmental dynamical control of tropical cyclone maximum potential intensity. The effects of the translational speed and vertical wind shear, on TC intensification and the lifetime peak intensity were analyzed based on observations in the WNP during 1981-2003. Both very intense TCs and TCs with RI are only found to occur in a narrow range of translational speeds between $3\text{--}8\text{ m s}^{-1}$, and in relatively weak vertical shear. The majority of WNP TCs reach their lifetime peak intensity just prior to recurvature where their environmental steering flow and vertical shear are both weak. Few TCs intensified when they moved faster than 15 m s^{-1} , or when their large-scale environmental vertical shear is larger than 20 m s^{-1} . The intensification rate of TCs is found to increase with decreasing vertical shear. The majority of the weakening storms experience relatively strong vertical shear. Based on statistical analysis, a new empirical maximum potential intensity (MPI) was developed, which includes the combined negative effect of translational speed and vertical shear as the environmental dynamical control in addition to the positive contribution of SST and the outflow temperature as the thermodynamic control. The new empirical MPI provides a more accurate estimation of TC maximum intensity and better explains the observed behavior of the TC maximum intensity. It improves our understanding of the thermodynamic and environmental dynamical controls on TC intensity.

5. On sea surface roughness parameterization and its effect on tropical cyclone structure and intensity. In this study, a parameterization scheme for sea surface momentum roughness length, applicable for all wind regimes including high winds under TC conditions, is constructed based on latest measurements from Global Positioning System (GPS) dropsondes. Most parameterizations used in models today are based on extrapolations from lower wind regimes up to only 25 m s^{-1} . Our new parameterization reproduces the observed regime transition, namely, an increase of the drag coefficient with the increase of wind speed up to 40 m s^{-1} followed by a decrease with further increase of wind

speed. Simulations of TCs with a new non-hydrostatic TC model – TCM4, show that although the intensification rate is not affected by the use of the new scheme compared with the traditional extrapolation, the final intensity is increased by 10.5% (8.9%) in the maximum surface wind speed and by 8.1 hpa (5.9 hpa) increase in the minimum sea surface pressure drop with (without) dissipative heating. This intensity increase is found to be mainly due to the reduced frictional dissipation in the surface layer and is not due to either the surface enthalpy flux or latent heat release in the eyewall convection. The effect of the new surface roughness parameterization on storm structure is found to occur only in the inner core region with the increase in tangential winds in the eyewall and the increase in temperature anomalies in the eye compared to the traditional extrapolation. Consistent with previous findings, dissipative heating increases the maximum TC intensity. Dissipative heating also affects the TC inner core structure considerably acting to shift the eyewall slightly inward and to reduce the slope of outward eyewall tilt with height. Although the dissipative heating acts to enlarge the intensity increase due to the use of the new surface roughness parameterization, it reduces the difference in storm structure to some degree.

6. Tropical cyclone changes in the western north Pacific in a global warming scenario. The influence of global warming on the climatology of TCs in the WNP basin is examined using the high-resolution IPRC regional climate model forced by ocean temperatures and horizontal boundary fields taken from the NCAR CCSM2 coupled global climate model. The model was run for ten years with forcing from a present-day control run of the CCSM2 and then for ten years with forcing fields taken from the end of a long run with six times the present day atmospheric CO₂ concentration. The global-mean surface air temperature warming in the perturbed run is 4.5 K, while the surface warming in the tropical western Pacific is about 3 K. The results reveal no statistically significant change in basin-wide TC numbers in the peak season from July to October due to the CO₂ increase. However, a pronounced and statistically significant increase in TCs occurred in the South China Sea. While the basin-wide total number of storms remains nearly unchanged in the warm climate, there is a statistically significant increase in the average strength of the cyclones and in the number of the storms in the strongest wind categories. This result supports the observed trend during the past 30 in the region.

7. A case study of equatorial genesis.

Typhoon Vamei formed at the unusually low latitude of 1.5° N in the South China Sea (SCS) in December 2001. This typhoon is the most near-equatorial TC reported by the Joint Typhoon Warning Center (JTWC 2002), confirmed by the measurement of sustained winds of 75 knots on a US naval ship. The aim of this study is to simulate this special equatorial TC genesis event using the fifth-generation national centers for atmospheric research (NCAR)/Penn State mesoscale model (MM5) to investigate dynamical and physical processes that resulted in cyclogenesis. During the first year of the research project, the model has been set up in the SCS region. The model was run for 96 hours, starting from 0000 UTC 24 December, 3 days prior to the TC formation. The model successfully simulated this near-equatorial TC genesis event. The simulated typhoon resembles the observed in the following aspects: 1) It had a short lifetime and a small size, 2) It formed near the equator (1.7°N), and 3) It reached category-one intensity. Given the success of the model simulation, our next step is to conduct a detailed diagnosis of the model output (including the TC vorticity budget) to investigate specific processes that lead to the TC genesis and to better understand the difference between the equatorial and off-equatorial cyclogenesis.

8. Large scale flow patterns and their influence on the intensification rates of western north Pacific tropical storms. Large scale environmental flow patterns around future intensifying tropical

storms are identified with the goal of finding the most favorable low-level flow fields for RI. The analysis is, based on the hypothesis that aspects of the horizontal flow may affect TC intensification at the early stage. A new initial intensity-based definition of RI is proposed and is used to define very rapid, rapid and slow 24 hr intensification periods from weak tropical storm stage (35 kts). By using composite analysis and scalar EOF analysis of the zonal wind around these subsets, a form of the lower level (850 mb) monsoon confluence pattern is found to occur dominantly for the very rapid cases. At 200 mb the importance of the location of the incipient tropical storm directly under a region of flow splitting into the mid-latitude westerlies to the north and the sub-equatorial trough to the south is identified as a common criterion for the onset of RI (as well as an eastward extension of outflow south of the TUTT). The total 200 mb slow composite exists in an upper level environment with north-easterlies over the lower level tropical storm, and without outflow to the north

9. Secondary eyewall formation in tropical cyclones in the presence of horizontally sheared environmental flow. Modeled secondary eyewall like features were found to appear in moist vortices in strong background horizontal shear. Using an anomaly version of TCM3 in which a TC vortex is placed in varying meridionally sheared background zonal flows (westerlies to the south of the vortex, easterlies to the north-resembling WNP background flow), secondary eyewall features develop when the meridional shear reaches a critical strength. The stronger advection of background flow tangential momentum by the secondary circulation of the vortices create a marked slowing of the radial decline of vortex tangential winds near the radius where the meridional gradient of the background flow is largest. Weak secondary tangential wind maxima creates an area of enhanced boundary layer frictional convergence and therefore leads to a persistent secondary convective area near this radius, which for a time dominates inner core convection. For strong horizontal shear the secondary vertical motion maximum becomes the primary feature and prevents the cyclone intensifying to the level of other cases with weaker background horizontal shear, by not allowing the inner eyewall to dominate. These findings raise interesting questions, regarding the formation of secondary eyewalls in TCs.

10. Climate variation and large-scale control of tropical cyclone intensification in western north Pacific. This study investigates climate variability of TC RI and formation over the WNP on annual, intraseasonal and interannual time scales. We found that the variability of RI activity is different to that of the TC formation. For instance, TC RI instances in August are relatively suppressed (30% of total TCs compared to a maximum of 47% in November), although the greatest number of TC form in this month. The high (low) ratio of RI in November (August) is attributed to the strong (weak) low-level environmental cyclonic shear and the southeast (northernmost) locations of TC formation. Further, TC RI activity is enhanced (suppressed) during El Nino (La Nina) years although the total TC formation number does not differ significantly. During the peak TC season (July, August and September), the mean number of RI in strong El Nino (La Nina) years is 7.1 (4.9) over the entire WNP and 3.0 (0.3) over the southeast quadrant (0-17°N, 140-180°E) of the WNP. During La Nina years, while more TCs form in the northwest quadrant (17-30°N 120-140°E), the RI was not enhanced significantly there. Not only the frequency but also the positions of the RI vary remarkably with the phases of the intraseasonal oscillation (ISO). When the WNP monsoon trough is enhanced, the number of RI in the core region of RI (8-20°N, 125-155°E) is 2.5 times that during an opposite phase of ISO. We show that the ISO signal over the *equatorial* western Pacific can act as a good predictor of WNP RI 10-25 days ahead.

IMPACT/APPLICATIONS

The development of the nonhydrostatic model TCM4 model provides a significant opportunity to study features of TCs requiring finer horizontal resolution and has potential for studying inner core processes responsible for intensity change that could not be resolved before.

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